Cluster Mergers and Diffuse Radio Emission in Abell 2256 and Abell 754

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We present deep VLA observations of the galaxy clusters Abell 2256 and Abell 754, both of which appear to be in the violent stage of major cluster merger events. The complex nature of Abell 2256 is revealed through radio images which, in addition to the head-tail galaxies, show two extended, irregular, and sharp-edged regions of diffuse radio emission at the cluster periphery (so called radio relics), and a large-scale diffuse radio halo located in the central regions of the cluster. Polarimetry of the A2256 cluster relics reveals large-scale ordered magnetic fields which appear to trace the bright filaments in the relics. The polarization fraction across the relics ranges from 20% - 40% with the majority of the relics polarized above the 30% level. At the sensitivity of our current observations we place an upper limit of 20% on the polarization of the radio halo. Low frequency VLA observations of Abell 754 reveal extended, diffuse radio (halo) emission in the cluster core region as well as steep spectrum emission in the cluster periphery. The location, morphology, and spectral index of the peripheral emission are consistent with the properties of radio relics. The X-ray evidence of the ongoing mergers in both clusters, together with the polarization properties of A2256's radio relics supports recent suggestions of a merger-induced origin of the relic emission. Deciphering the complex radio properties of these clusters may thus provide the key to understanding the dynamical history of the systems.

1 Introduction

In the hierarchical model of structure formation objects form from the collapse of initial density enhancements and subsequently grow through gravitational effects. Numerical simulation of structure formation show that clusters of galaxies are found to preferentially form at the intersection points of large filamentary structures [40,24]. Due to the high-density environment in which they reside, clusters of galaxies are thus expected to undergo several merger events as they form. These merger events are highly energetic ($10^{63} - 10^{64}$ ergs) and thus provide a significant energy input into the intracluster medium (ICM). Large scale structure simulations [28] as well as recent 3D MHD/N-body simulations [30,31] find that the shocks and turbulence associated with a major cluster merger event can significantly amplify the intracluster magnetic field and accelerate relativistic particles which, in the presence of a magnetic field, emit synchrotron emission.

1.1 Diffuse Radio Emission in Galaxy Clusters

Radio observations toward a number of galaxy clusters reveals the presence of large regions of diffuse radio emission which extend over scales of > 600 kpc in the ICM and have no obvious

optical counterpart. This emission appears to fall in two categories: *halos* which are centrally located in the cluster, relatively regular in shape, and unpolarized, and *relics* which are peripherally located, fairly elongated and irregular, and often highly polarized [12].

The presence of these large regions of diffuse synchrotron emission reveals the large scale distribution of relativistic particles and magnetic fields in the intracluster medium. Despite extensive searches through the NRAO VLA Sky Survey [16] and the Westerbork Northern Sky Survey [25] as well as a number of targeted searches for radio halos and relics [15,39,29,35,11,18,7,17,26,23] there are still a relatively small number of clusters known to contain this emission. We must therefore ask: Why are these sources so rare? Do the known clusters contain excess magnetic fields? Do they contain a larger reservoir of relativistic particles than other clusters? or perhaps they have excess particles and magnetic fields?

Many, if not all, of the galaxy clusters which are confirmed to contain diffuse radio emission also show significant evidence of merger activity. The clusters which contain radio halos tend to be very X-ray luminous, massive clusters [6,26,4] which display a significant amount of X-ray substructure. Although this suggests that the merger event is the trigger for the diffuse emission, it should be noted that only 10% of galaxy clusters appear to contain diffuse emission while more than 40% of clusters show evidence of merger activity [21].

2 Abell 2256, a Mpc^3 Non-Thermal Laboratory

2.1 Two or Three Body Merger System?

Abell 2256 is a rich, nearby (z=0.0594) cluster of galaxies and was one of the first targets observed by ROSAT. Analysis of these observations [3] revealed significant substructure in the cluster. The X-ray surface brightness distribution shows two separate X-ray peaks that indicate it is undergoing a merger event. The X-ray temperature map of the cluster [2] shows that the infalling component is cooler than the main cluster body and that there are two hot regions roughly perpendicular to the merger axis. These hot regions are similar to those seen in simulations of merger events where the merger has not yet proceeded past core passage [33,32]. The ROSAT view of the cluster is thus a two body merger which is approximately 1 Gyr before core passage.

Although the two body merger model fits the X-ray data quite well, it will be seen below that the radio data are very hard to understand in this scenario. A couple of days before the Moriond meeting, a Chandra paper on Abell 2256 appeared on *astro-ph* [36] which showed a new structure was visible in the X-ray surface brightness map in addition to the merging component found by ROSAT. This feature is located close to the core of the cluster and is interpreted as either another merging component, or an internal structure to the main cluster. If the new feature found by Chandra is interpreted as a merger signature, comparison of the the X-ray images to cluster merger simulations [37,38] suggests that is may be an old merger which is ~ 0.3 Gyr after core passage. In this scenario, Abell 2256 is a three-body merger system where the oldest merger has proceeded significantly far as to only be visible as an X-ray excess near the cluster core, while the current merger is still in the early stages and has not significantly disrupted the cluster gas. This merger history fits much better with the observed radio properties of the cluster.

Further X-ray observations of the A2256 cluster with BeppoSAX reveal the presence of a hard X-ray tail. Such emission has been detected in Coma [14] and Abell 2199 [22] and is generally interpreted as non-thermal inverse Compton (IC) emission from relativistic electrons scattering off the cosmic microwave background (CMB) photons. Such a model requires that there be a large reservoir of relativistic electrons in the intracluster medium. In the presence of a magnetic field, these electrons will radiate synchrotron emission and should be visible in the radio regime.

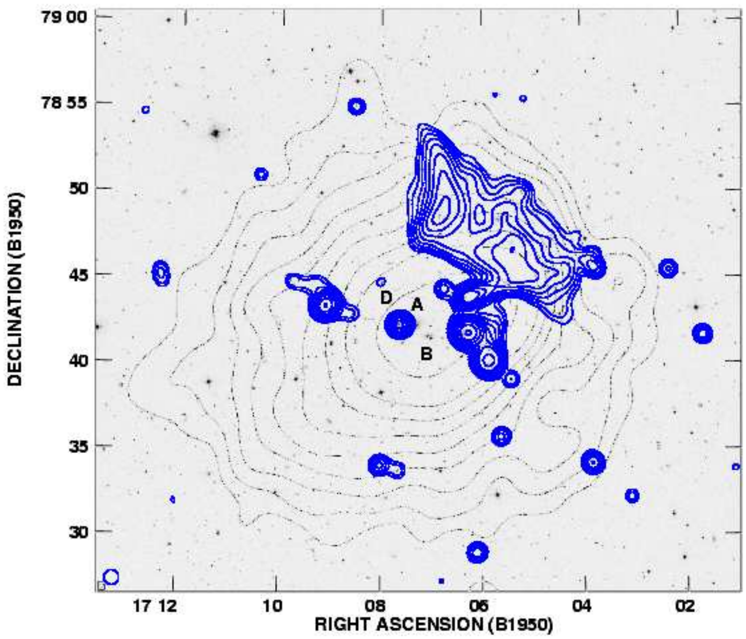

Figure 1: Digital Sky Survey R-band greyscale image overlaid with smoothed ROSAT PSPC contours (black) and VLA 1.4 GHz contours (blue). The galaxy notation in the figure is that of Sun et al. (2001). At the redshift of A2256, the linear scale is $\sim$ 1.1 kpc/arcsec for $H_o = 75$ km s^{-1} Mpc^{-1}.

2.2 Radio Emission

Previous radio observations of Abell 2256 [1,34] have revealed that it has very complex radio emission. The cluster contains a number of head-tail galaxies, two large regions of diffuse radio relic emission, and also possibly a central radio halo. In order to obtain a better understanding of the complex radio emission in this cluster, we have undertaken deep NRAO VLA[a] observations in several configurations of Abell 2256 at a number of different frequencies ranging from 4.8 GHz to 330 MHz. In this paper we discuss the results from observations at 1.4 GHz in the VLA's C and D configurations.

In Figure 1 the smoothed ROSAT X-ray contours of A2256 are plotted over the R-band image from the Digitized Sky Survey (DSS). Also shown on the image are the VLA 1.4 GHz radio contours which reveal the compact and head-tail sources as well as the radio relics. This ROSAT overlay can be compared to Figure 1 of Sun et al. (2001) which shows the DSS plus radio and Chandra contours. There are three bright optical galaxies seen at the cluster center: galaxy 'D' in the notation of Sun et al. (2001) which corresponds to the bright compact radio source in the center of the image, the cluster center elliptical ('B') which is located $\sim$ 2' south-west, has no radio counterpart, and is only 0'.5 away from the central X-ray peak, and galaxy 'A' which has a very extended optical halo but has not obvious radio counterpart.

We have undertaken deep VLA observations of the complex radio emission in Abell 2256 at four frequencies around 20 cm and two frequencies around 6 cm with the VLA. These observations were undertaken in the compact C and D configurations in order to provide the sensitivity required to detect the diffuse, large-scale emission typical of cluster halos. Figure 2 shows the 1369 MHz VLA D configuration total intensity image. The compact and head-tail sources in the cluster are clearly visible along with the large regions of diffuse radio emission. The elongated bright region to the north-west is identified as radio relics G (the Eastern relic) and H

[a]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

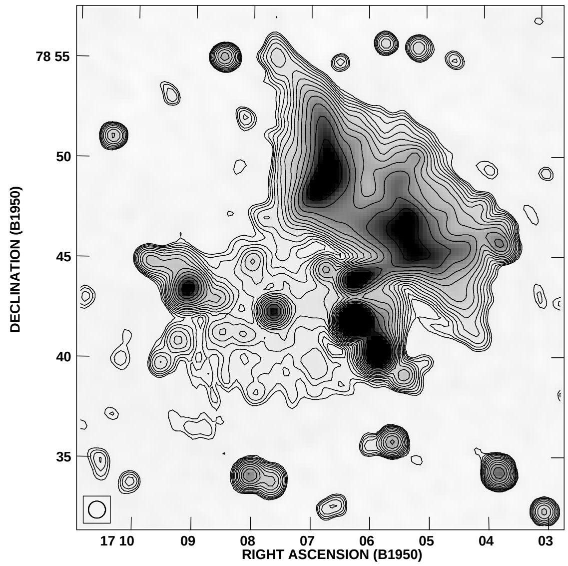

Figure 2: VLA 1369 MHz D configuration total intensity greyscale and contours. Both the peripheral radio relics and central radio halo emission are clearly visible.

(the Western relic) in the notation of Bridle & Fomalont (1976). The image also reveals a large central halo in the cluster which was previously marginally detected [1] but clearly extends to over 300 kpc in radius.

The VLA observations show that the radio relics extend over a region of 975 kpc × 650 kpc and appear to have a sharp edge to the emission. Embedded with the relic structures are relatively bright filamentary structures which appear to have widths of around 100 kpc in the brighter G relic. The relics are highly polarized with the linear polarization fraction above 30% for the majority of the region and reaching values of up to 50%. The intrinsic magnetic field direction shown in Figure 3 reveals that there is large scale order to the fields, and it appears to trace the bright filaments in the relics. The spectral index across the G relic is remarkable uniform at -1.0 ($S_\nu \propto \nu^\alpha$) between 20 cm and 6 cm. This spectral index is steeper than the value of -0.37 found between 90 cm and 20 cm by Rottgering et al. (1994) but is in good agreement with the more recent [25] value of -1.25 reported between 90 cm and 20 cm.

The radio halo appears to be offset from the cluster core, and is centered roughly around a compact radio source which corresponds to galaxy 'D' in Figure 1. The halo emission is very uniform, relatively symmetric, and shows no obvious edge. At the sensitivity of our current observations, we place an upper limit of 20% on the linear polarization of the halo. The halo appears to be very steep spectral index emission, and we estimate a spectral index of $\sim$ -2.0 between 20 cm and 6 cm.

The position of the emission for the radio relics is roughly co-incident with the location of the merging subcluster to the north-west of the cluster core. The radio halo on the other hand appears to be centered about the current location of the old merger remnant to the west of the cluster core. The relatively flat spectral index of the relic emission suggests that the relativistic particles may have recently been injected in the region or have undergone an acceleration process. This is consistent with the picture that the on-going merger event has recently shock-accelerated the particle population in the north-west quadrant of the cluster [8,9]. The high polarization fraction and alignment of the magnetic fields are consistent with shock

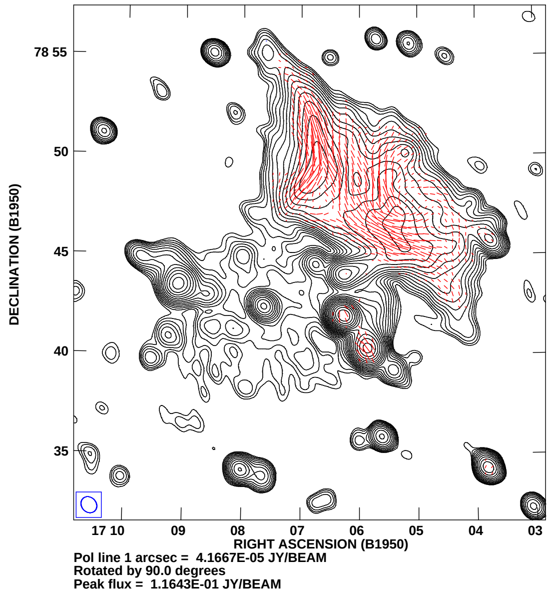

Figure 3: VLA 1369 MHz D configuration contours of Abell 2256 with the Faraday corrected magnetic field vectors overlaid.

compression of an old magnetized plasma [8,10]. The steeper spectral index of the halo indicates that it has not recently received a fresh population of relativistic particles. This is consistent with the scenario of the halo formation from the earlier merger event.

3 Abell 754

Abell 754 is another well studied galaxy cluster which shows significant optical [41] and X-ray [20,19] evidence of a major merger event. This article will not go into details on the observations of this cluster as they are presented elsewhere in these proceedings [5] and in the literature [23]. The overall picture [27] from optical and X-ray observations of the A754 system suggests that is undergoing a three body merger similar to Abell 2256. Low frequency radio observations of the cluster reveal a diffuse radio halo slightly offset from the cluster core, and possibly two steep spectrum radio relics in the cluster periphery located on either side of the cluster core. One of these relics (the eastern relic) lies on the ram pressure flattened edge of the X-ray bar suggesting a connection with the on-going merger event.

4 Summary

Both Abell 2256 and Abell 754 display very complex radio emission. Although radio halos and relics are still relatively rare, both of these are found in the apparent three body merger systems A2256 and A754. It is becoming increasingly evident that the diffuse radio emission in galaxy clusters is indeed related to major cluster merger events. Combining optical, high resolution X-ray, and radio observations of cluster systems can provide significant insight into the merger history of the clusters. The radio and X-ray data also place constraints on the relative dynamical roles of thermal and nonthermal plasma components of the intracluster medium.

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